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First Real-Time 267.8 Tb/S 2 × 70.76 Km Integrated Communication and Sensing Field Trial over Deployed Seven-Core Fiber Cable Using 130 Gbaud PCS-64QAM 1.2 Tb/S OTN Transponders

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Abstract: Ultra-high-speed integrated communication and sensing (ICS) transmission techniques are highly desired for next-generation highly reliable optical transport networks (OTNs). The inherent multiple-channel advantage of uncoupled multi-core fibers (MCFs) empowers the evolution of ICS techniques. In this paper, we demonstrate an ultra-high-speed ICS OTN system utilizing 130 Gbaud probability constellation shaping 64-ary quadrature amplitude modulation (PCS-64QAM) 1.2 Tb/s OTN transponders and polarization-based sensing technique over a field-deployed seven-core MCF cable for the first time. A real-time 267.8 Tb/s 2 × 70.76 km transmission is achieved by only utilizing C-band signals thanks to the high-performance 1.2 Tb/s OTN transponders. Moreover, the ICS system can sense environmental impacts on the MCF cable such as shaking, striking, etc., in real time. The capacity of the transmission system can also be further enhanced by using signals in the L-band. Our work demonstrates the feasibility of simultaneously achieving ultra-high-speed data transmission and the real-time sensing of environmental disturbances over a field-deployed MCF cable, which we believe is a crucial milestone for next-generation ultra-high-speed highly reliable optical transmission networks.

Keywords: space-division multiplexing; multi-core fiber; real-time transmission; optical network; field trial

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Received: 7 May 2025
Revised: 3 June 2025
Accepted: 5 June 2025
Published: 6 June 2025

Citation: Cui, J.; Zhang, L.; Deng, Y.; Liu, Z.; Wu, C.; Hao, B.; Zhang, T.; Wang, Y.; Wu, B.; Zhang, C.; et al. First Real-Time 267.8 Tb/S 2 × 70.76 Km Integrated Communication and Sensing Field Trial over Deployed Seven-Core Fiber Cable Using 130 Gbaud PCS-64QAM 1.2 Tb/S OTN Transponders. *Photonics* **2025**, *12*, 577. https://doi.org/10.3390/photonics12060577

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1. Introduction

With the unprecedented expansion of high-quality network applications such as computility networks and financial dedicated network services, there is a growing demand for high-speed highly reliable optical interconnection systems. To ensure the operational security of high-speed optical transmission networks, the transmission system needs to

be capable of sensing external disturbances to the optical fiber cable, thereby providing advance warnings of potential failures and performing switching operations. In order to achieve this ability, integrated communication and sensing (ICS) techniques have attracted significant attention and been widely investigated, and they can offer a dual functionality in terms of high-speed data transmission and real-time environmental monitoring (e.g., temperature, strain, and vibration detection) [1]. The additional sensing ability of ICS systems enables the real-time acquisition of environmental parameters or the prediction of potential failures, and it can find applications in smart cities, industrial automation, and infrastructure health management [2,3]. However, traditional optical fiber sensing methods will inevitably occupy communication channels, posing a formidable challenge to simultaneously achieving ultra-high-speed transmission in existing optical communication systems based on widely deployed single-mode fibers (SMFs) [4,5]. Although constructing more optical fiber cables can, to some extent, solve the problem of insufficient transmission capacity and meet the bandwidth requirements for sensing, it is extremely costly and will occupy a large amount of spatial resources. Recently, space-division multiplexed (SDM) transmission techniques utilizing few-mode fibers (FMFs), multi-mode fibers (MMFs), or multi-core fibers (MCFs) have been widely investigated and are considered promising solutions for supporting capacity-consuming services in next-generation optical networks [6–8]. Similar to mature wavelength-division multiplexed (WDM) transmission systems, the multiple parallel spatial channels (e.g., fiber modes or fiber cores) within a single fiber cladding can multiply the transmission capacity of a single fiber without significantly increasing its size. In terms of the types of utilized optical fibers, there are two technical routes for achieving SDM transmission. For the mode-division multiplexed (MDM) technical route using FMFs or MMFs, a record ultra-large-capacity transmission is achievable due to the abundant mode resources [9–11]. However, costly multiple-input multiple-output digital signal processing (MIMO-DSP) is required at the receiver to eliminate the inevitable modal crosstalk induced by mode multiplexers/demultiplexers and fiber transmission to achieve ultra-high-speed long-haul transmission, which hinders direct compatibility with existing high-speed optical modules [12]. In contrast, the core-division multiplexed (CDM) approach using MCFs suppresses inter-core crosstalk easily, because different SDM signals are transmitted over separate fiber cores, enabling long-haul transmission and compatibility with existing optical modules via fan-in/fan-out (FIFO) devices [13,14].

In the past decade, high-speed transmission and effective fiber maintenance technologies based on uncoupled MCFs have been widely investigated, and multiple remarkable breakthroughs have been made. For example, an advanced four-core fusion splicing technique utilizing a precise azimuthal alignment algorithm and a three-electrode arc-discharging splicer has been reported, demonstrating an average splicing loss of less than 0.03 dB [15]. Regarding FIFO devices, multiple precise fabrication methods, such as fiber bundle alignment or femtosecond laser direct writing, have been proposed and experimentally demonstrated, enabling the implementation of various MCFs with different numbers of fiber cores [16,17]. With the gradual maturity of MCF-based techniques, real-time CDM transmission using commercial 400 Gb/s optical transport network (OTN) transponders, as well as multiple field trials over experimental MCF cables, have been demonstrated [2,13,18,19]. These works undoubtedly prove the feasibility of integrating MCFs into next-generation optical networks and promote the field implementation of MCFs in terrestrial optical fiber cable systems. Furthermore, benefiting from the inherent advantage of MCFs that they contain multiple parallel fiber core channels within a single fiber, MCFs can also enable various capacity-consuming services, especially ICS techniques. The multiple fiber core channels in an MCF provide sufficient channel resources for simultaneously achieving sensing functions, and multiple MCF-based ICS systems have been

reported. For instance, a full-duplex ICS system utilizing distributed fiber sensors over the spare cores of MCFs has been demonstrated, which is compatible with commercial optical modules as well as fiber sensors, and it can realize the real-time monitoring of environmental parameters [20]. Additionally, a field trial of high-resolution distributed fiber sensing over MCF cable in the city of L'Aquila, Italy, using a MIMO distributed acoustic sensing (DAS) technique has been reported [1]. Leveraging the multiple parallel core channels in an MCF and advanced MIMO-DAS, the system achieves a 2 m spatial resolution and 1 mHz–380 Hz acoustic bandwidth, which can effectively localize and identify construction-related events in metropolitan areas. In addition, a high-speed field trial of an ICS system over deployed seven-core fiber cable has also been experimentally demonstrated, which reached a large capacity of 234 Tb/s (net 187.49 Tb/s) while monitoring traffic surrounding the deployed MCF cable [2]. These remarkable MCF-based ICS techniques significantly advance the evolution of optical networks toward a large capacity and high operational security. However, to the best of our knowledge, a real-time field trial of an ultra-high-speed ICS transmission system using 1.2 Tb/s OTN transponders over deployed MCF cable has not been reported so far. Fully exploring the transmission capacity and sensing potential of MCFs, and promoting their field implementation in next-generation ultra-high-speed highly reliable optical transmission networks, is highly desired.

In this paper, we demonstrate an ultra-high-speed ICS OTN system utilizing 130 Gbaud probability constellation shaping 64-ary quadrature amplitude modulation (PCS-64QAM) 1.2 Tb/s OTN transponders and dual-polarization quadrature phase shift keying (DP-QPSK) 200 Gb/s ICS optical transponder units (OTUs) with polarization-based sensing techniques over a field-deployed seven-core fiber cable for the first time. A real-time 267.8 Tb/s 2 $\times$ 70.76-km transmission is achieved using only C-band signals thanks to the high-performance 1.2 Tb/s OTN transponders. And the ICS system can sense environmental disturbances to the MCF cable such as shaking, striking, and so on in real time through the 200 Gb/s ICS OTUs by monitoring the changes in the polarization state of the received signals. The transmission capacity can also be further enhanced by incorporating L-band signals. This work demonstrates the feasibility of simultaneously achieving ultra-high-speed data transmission and the real-time sensing of environmental disturbances over field-deployed MCF cable and is beneficial to next-generation ultra-high-speed highly reliable optical transmission networks.

The rest of this paper is organized as follows. In Section 2, we present our proposed ultra-high-speed MCF-based ICS OTN prototype system. Section 3 shows the ultra-high-speed 130 Gbaud 1.2 Tb/s OTUs and the 200 Gb/s ICS OTUs utilized in our field trial. In Section 4, the field-deployed seven-core MCF cable is introduced. Section 5 presents the experimental results of the field trial. More in-depth discussions and prospects regarding the ultra-high-speed ICS CDM transmission system are provided in Section 6. Finally, Section 7 concludes the paper.

2. Ultra-High-Speed MCF-Based ICS OTN Prototype System

In this section, we present our proposed ultra-high-speed MCF-based ICS OTN prototype system, whose architecture is shown in Figure 1. The extremely high bit rate of the system is achieved through next-generation single-wavelength 1.2 Tb/s OTUs and a CDM transmission technique based on 7-core fibers. The ICS capability of the system is enabled by 200 Gb/s ICS OTUs, which can perform the real-time monitoring of environmental disturbances (e.g., shaking and striking) to optical fiber cable while transmitting data. Specifically, at the transmitter station, multiple 1.2 Tb/s OTUs are utilized to transmit ultra-high-speed modulated signals in the C-band, and a 200 Gb/s ICS OTU is employed to transmit ICS signals. The optical signals emitted by these OTUs exhibit distinct cen-

tral wavelengths and are multiplexed through a wavelength selective switch (WSS). An Erbium-Doped Fiber Amplifier (EDFA) is used to amplify the multiplexed signals, which are then coupled to a fiber core of the 7-core fiber for CDM transmission via a FIFO device. The total transmission link consists of multiple CDM transmission links, each composed of a pair of FIFO devices and a span of 7-core fiber. The FIFO devices facilitate mutual coupling between the 7-core fiber and multiple SMFs. And 7 sets of single-mode (SM) EDFAs are employed between every two CDM transmission links to amplify the 7-channel CDM optical signals. After transmission over multiple CDM links, each path of received WDM signals from the FIFO device is first amplified by an EDFA at the receiver station, and another WSS is used to demultiplex the WDM signals. The demultiplexed signals are then sent to the corresponding OTUs for coherent reception. The 1.2 Tb/s OTUs at the receiver perform a real-time DSP and bit error rate (BER) calculation on the received signals to achieve ultra-high-speed data transmission. Unlike the 1.2 Tb/s OTUs, the 200 Gb/s ICS OTU simultaneously detects the optical status of received signals to sense external environmental disturbances to the MCF cable when performing DSP at the receiver. Considering the structural characteristics of MCFs, where multiple fiber cores are integrated within a single cladding, the ICS signal transmitted through one fiber core is sufficient to sense environmental disturbances affecting the entire MCF. Therefore, as illustrated in Figure 1, in our proposed MCF-based ICS prototype system, only the central core of the 7-core fiber is equipped with a pair of 200 Gb/s ICS OTUs for environmental monitoring, while the remaining six fiber cores are used to transmit ultra-high-speed 1.2 Tb/s optical signals.

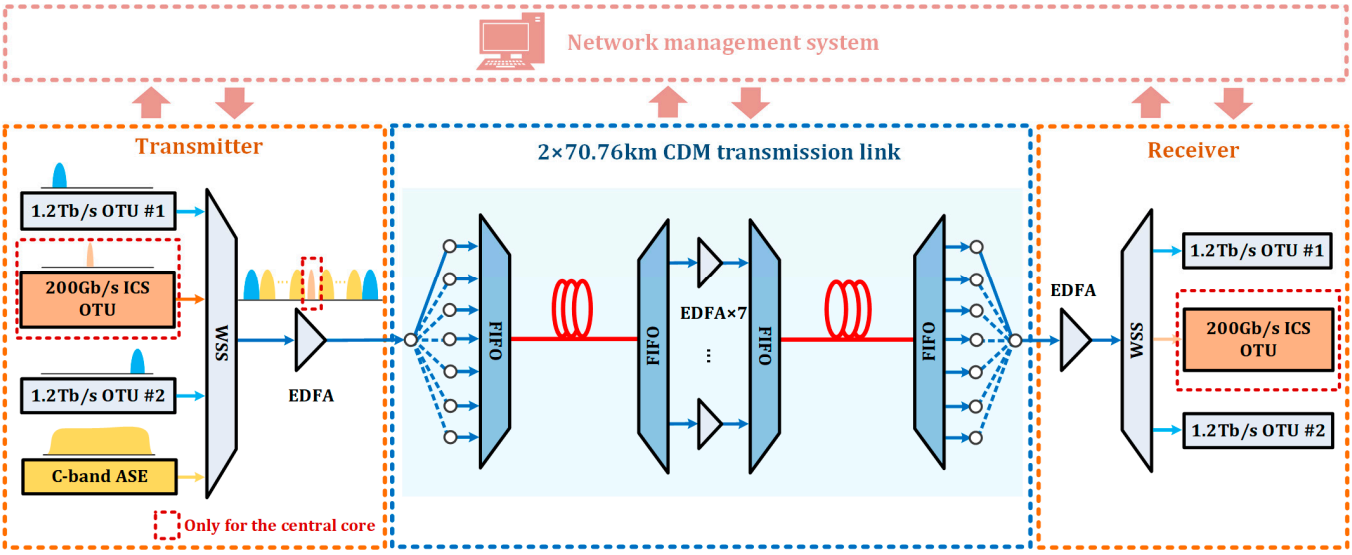

Figure 1. Architecture of the ultra-high-speed MCF-based ICS OTN prototype system.

It should be emphasized that, as shown in Figure 1, due to the lack of sufficient ultra-high-speed 1.2 Tb/s OTUs in the field trial, we employ two pairs of 1.2 Tb/s OTUs with different central wavelengths to test the transmission performance of each fiber core channel. Other wavelength channels in the C-band are filled with white noise generated by a C-band amplified spontaneous emission (ASE) source to simulate a fully loaded C-band WDM transmission. The power of the ASE signal that filled in each wavelength channel is identical to that of each modulated signal emitted by the OTU, and the multiplexing of modulated signals and ASE signals is also performed through the WSS. In our field trial, we test the performance of each fiber core channel individually, which is achieved by manually connecting the output SM pigtail of the transmitter to different input ports of the FIFO device one by one. The remaining six fiber cores are fully populated with C-band ASE signals to simulate a CDM transmission. This is achieved by launching C-band ASE signals

into the remaining six fiber core channels through the FIFO device. Moreover, considering the length of available MCF cables, the entire transmission link consists of two 70.76 km CDM transmission links in the field trial. All the transmission equipment, including OTUs, WSSs, and EDFAs, are connected to the network management system, which enables the online parameter configuration of each device. Moreover, the real-time BER values and alarms for detected environmental disturbances can also be directly obtained from the network management system.

3. Ultra-High-Speed 1.2 Tb/S OTU and 200 Gb/S ICS OTU

In this section, we introduce the ultra-high-speed 1.2 Tb/s OTU and 200 Gb/s ICS OTU used in our field trial. The 1.2 Tb/s OTU has a modulation rate of up to 130 Gbaud, which enables the adoption of a PCS-64QAM modulation format to achieve the ultra-high bit rate. The central wavelength of the 1.2 Tb/s OTU is tunable from 1529.553 nm to 1566.723 nm, with a channel spacing of 150 GHz, and it can support a maximum of a 32-wavelength WDM transmission over the C-band. This OTU can also dynamically adjust its bit rate by changing the modulation format. For example, the bit rate can be adjusted to 800 Gb/s by using the PCS-16QAM modulation format. The 200 Gb/s ICS OTU adopts the DP-QPSK modulation format with a 67 Gbaud modulation rate. Its central wavelength is also tunable over the C-band, with a channel spacing of 75 GHz. The soft-decision forward error correction (SD-FEC) limit for these OTUs is 2.88×10^{-2}. Figure 2a shows an interior photo of the test site. The under-test transmission equipment, including the 1.2 Tb/s OTUs, etc., are installed in the equipment rack, and the network management system is utilized to manage the OTN equipment as mentioned before. A photograph of the 200 Gb/s ICS OTUs at the test site is also depicted in Figure 2b.

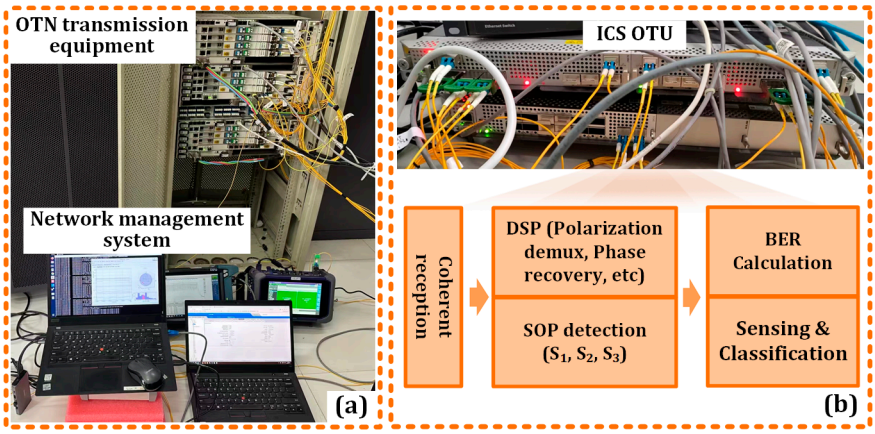

Figure 2. (**a**) Interior photo of the test site. (**b**) Photograph of 200 Gb/s ICS OTUs and the signal processing flow at the receiver.

The 200 Gb/s ICS OTU realizes the sensing of environmental disturbances to the MCF cable by detecting and analyzing the variations in the state of polarization (SOP) of the received optical signal during DSP processing. The SOP detection process is synchronous with the DSP and enables the system to simultaneously sense environmental disturbances while receiving transmitted data. The detected SOP is represented by normalized Stokes parameters S_1, S_2, and S_3, which are defined as follows:

$$S_1 = (I_x - I_y)/I_{total}, \quad (1)$$

$$S_2 = (I_{+45^\circ} - I_{-45^\circ})/I_{total}, \quad (2)$$

$$S_3 = (I_R - I_L)/I_{total}, \quad (3)$$

where I_x, I_y, I_{+45°, I_{-45°, I_R, and I_L are the intensities of the horizontally linearly polarized component, vertically linearly polarized component, linearly polarized component in the $+45^\circ$ direction, linearly polarized component in the -45° direction, right-handed circularly polarized component, and left-handed circularly polarized component of the received signal light, respectively. And I_{total} is the total intensity of the received signal light. The 200 Gb/s ICS OTU at the receiver continuously acquires the normalized Stokes parameters S_1, S_2, and S_3 of the received optical signals while performing DSP, and it further analyzes the characteristics of SOP variations through a trained convolutional neural network (CNN). The CNN can determine whether the MCF cable is affected by environmental disturbances and classify the type of disturbances based on the detected SOP of the received signal. The CNN is trained using data from multiple laboratory tests. And during the training process, the focus is primarily on enabling the CNN to recognize and classify three types of environmental disturbances: shaking, periodic vibration, and striking. This CNN enables the ICS transmission system to provide early warnings for optical cable faults. By further incorporating test data involving more types of environmental disturbances such as squeezing or pulling into the training process, this CNN will gain the ability to sense and classify a wider variety of disturbances. It should be noted that the main difference between this 200 Gb/s ICS OTU and existing OTUs lies in the receiver. The polarization property of the transmitted signal is consistent with that of existing polarization-multiplexed (PM) coherent optical transmission systems. It comprises two single-polarization modulated signals in horizontal and vertical polarizations, which are combined by a polarization beam combiner (PBC). And this sensing method is based on monitoring and analyzing the SOP of the received signals, thus it will not occupy extra transmission channels and has almost no impact on data transmission.

4. The Field-Deployed Seven-Core MCF Cable

The performance of our proposed ultra-high-speed MCF-based ICS OTN prototype system is investigated over a field-deployed 7-core fiber cable, which is deployed in Jinan, China, with the route shown in Figure 3a. Based on available cable-laying resources such as utility poles and pipelines, the MCF cable is deployed using a combination of three methods including direct burial, overhead installation, and pipeline laying. Figure 3b presents a photograph of part of the overhead-installed MCF cable. The MCF cable has a total length of 17.69 km and is formed by fusion-splicing 11 segments of short cables. The length of each segment of short MCF cable is depicted in Figure 3c. The number of short MCF cables and the length of each short cable are also designed according to available cable-laying resources. The MCF cable contains eight identical 7-core fibers, and the cross-section of the 7-core fiber is illustrated in Figure 3a. The numbering of the fiber cores in Figure 3a matches that used in our subsequent field trial. And the third fiber core is the central core that will be employed with 200 Gb/s ICS OTUs to enable the real-time sensing of environmental disturbances. The fiber cladding and coating diameters are 150 μm and 245 μm, respectively. The fiber cladding diameter is designed to be larger than that of conventional SMFs, primarily to ensure a sufficient distance between different fiber cores and thereby suppress inter-core crosstalk. However, the overall coating diameter of the 7-core fiber remains compliant with existing standard SMFs, which ensures compatibility with legacy cabling processes while achieving a sevenfold increase in core density within the optical cable. Each fiber core in the 7-core fiber is non-polarization-maintaining (non-PM) and complies with the ITU-T Recommendation G.657. And low-refractive index fluorine-doped trenches are assigned to each fiber core, which can suppress light leakage from the fiber core and thus reducing inter-core crosstalk as well as bending loss. To further prevent misconnections between different fiber cores during fusion-splicing processing, a tiny marker core is

integrated into the MCF. Besides the parameters of the 7-core fiber already introduced, its remaining key characteristics after cabling are listed in Table 1. These characteristics are measured at 1550 nm. We find that the measured characteristics are close to those of the SMF cable, and the inter-core crosstalk is rather low and will have a negligible impact on transmission performance.

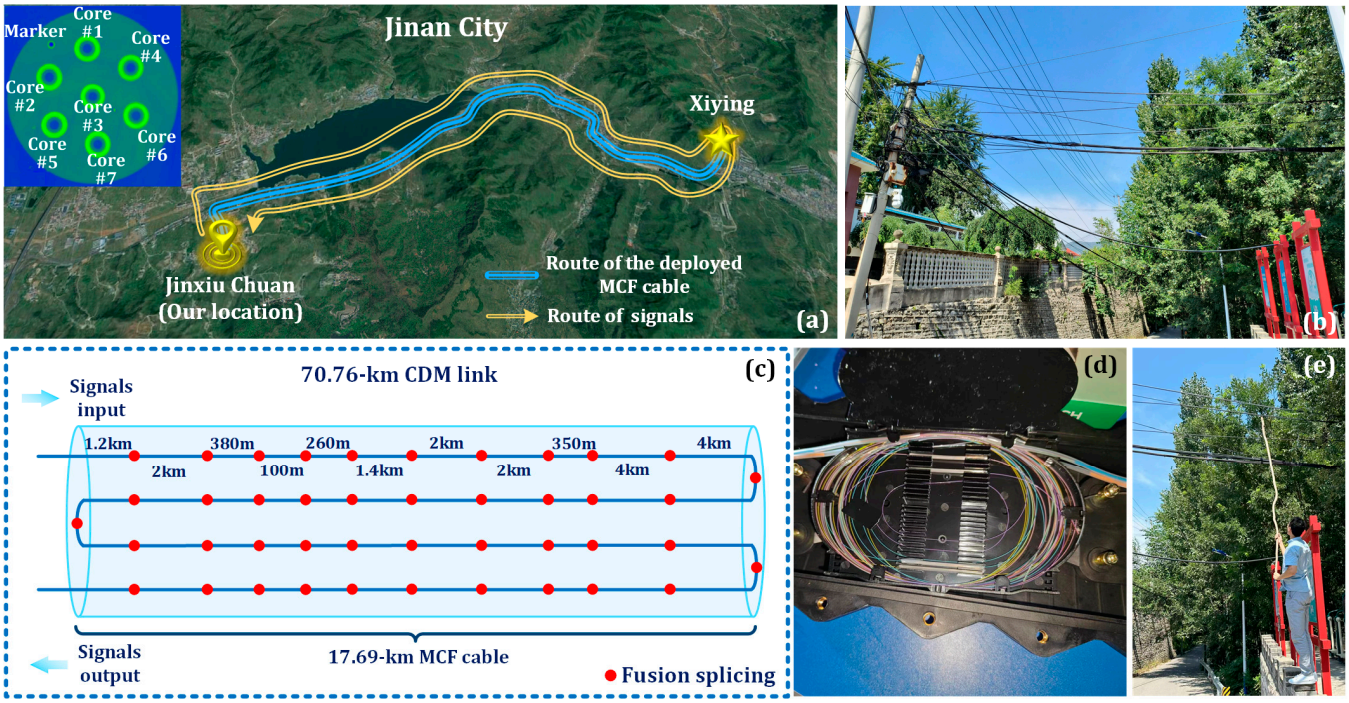

Figure 3. (**a**) Route of the deployed MCF cable and the cross-section of the 7-core fiber. (**b**) Photograph of overhead-installed MCF cable. (**c**) The structure of the 17.69 km MCF cable composed of 11 segments of short MCF cables, and the schematic diagram of the 70.76 km 7-core fiber link. (**d**) Photograph of a fusion-splice point within the fiber cable. (**e**) Photograph of testing the sensing ability of the ICS transmission system.

Table 1. Measured key characteristics of the 7-core fiber after cabling.

Core-to-Core Distance (μm)	Mode Field Diameter (μm)	Dispersion Coefficient (ps/nm/km)	Attenuation Coefficient (dB/km)	Cut-Off Wavelength (nm)	Polarization Mode Dispersion (ps/km$^{1/2}$)	Inter-Core Crosstalk (dB/10 km)	Bending Loss with R = 30 mm (dB/100 Turns)
42	9.0	≤22	≤0.22	≤1300	≤0.08	≤−50	<0.1

In our field trial, to fully explore the transmission capability of our system, we cascade every four of the eight 7-core fibers in the MCF cable to form two segments of 70.76 km 7-core fiber links. The cascading approach and the schematic diagram of the 70.76 km 7-core fiber link are depicted in Figure 3c. This cascading method also ensures that the transmitting and receiving stations are located in the same data center, which will facilitate the conducting of our experiment. The two segments of 70.76 km 7-core fiber links contain a total of 86 fusion splicings, which is similar to the widely deployed SMF cables. A photograph of a fusion-splice point within the fiber cable is shown in Figure 3d. Using an optical time-domain reflectometer (OTDR) and a FIFO device, we measure the loss of each fusion splicing at 1550 nm. The results show that the splicing losses are all less than 0.5 dB, and the average fusion-splicing loss is no more than 0.18 dB. We further connect each 70.76 km 7-core fiber with a pair of FIFO devices to construct two 70.76 km CDM links for optical link performance testing and the subsequent field trial of the ultra-high-speed

ICS OTN transmission system. The structure of the two 70.76 km CDM links is depicted in Figure 1. We measure the span loss and the total inter-core crosstalk of the two CDM links, and the results are shown in Tables 2 and 3, respectively. The total inter-core crosstalk is defined as the sum of crosstalk from all the other fiber cores to the core under test. We find that the span loss and the inter-core crosstalk are no more than 25.7 dB and −42.5 dB, respectively, for each fiber core channel. And the span loss is obviously larger the that of existing SMF cable of an equivalent length, which is primarily due to the higher splicing losses inherent in MCF compared to conventional SMF. It can also be found that span losses are slightly larger than those in our previous work [21]. This is mainly because the FIFO devices and their SM pigtails were squeezed before the field trial, resulting in a deterioration in their performance.

Table 2. Span loss and the total inter-core crosstalk of the first 70.76 km CDM link (Unit: dB).

	Core #1	**Core #2**	**Core #3**	**Core #4**	**Core #5**	**Core #6**	**Core #7**
Span loss	25.3	24.2	20.1	23.9	24.1	23.8	25.7
Total crosstalk	−47.1	−44.3	−42.7	−48.2	−46.2	−44.3	−47.5

Table 3. Span loss and the total inter-core crosstalk of the second 70.76 km CDM link (Unit: dB).

	Core #1	**Core #2**	**Core #3**	**Core #4**	**Core #5**	**Core #6**	**Core #7**
Span loss	25.1	25.3	19.8	23.8	25.2	23.2	24.6
Total crosstalk	−45.5	−45.3	−43.1	−46.8	−42.5	−46.6	−45.4

5. Experimental Results of the Ultra-High-Speed ICS CDM Transmission System

In this section, we present the experimental results of our ultra-high-speed ICS CDM transmission system utilizing 130 Gbaud 1.2 Tb/s OTUs and 200 Gb/s ICS OTUs over the field-deployed MCF cable. We first investigate the BER performance of each fiber core channel using 1.2 Tb/s OTU transceivers. Three wavelength channels with central wavelengths of 1529.55 nm, 1549.72 nm, and 1566.72 nm are selected to evaluate the system performance over the C-band. The three tested wavelength channels are successively denoted as λ_1, λ_2, and λ_3, respectively. And the three wavelength channels are realized by adjusting the central wavelengths of the two available 1.2 Tb/s OTUs. The single-wavelength input power to each fiber core channel of the two CDM links is uniformly set to 8 dBm. And ASE signals with the same single-wavelength input power are filled into all the remained wavelength channels, as previously mentioned. The seven fiber core channels are tested one by one using the same approach, and the results of the three tested wavelength channels after 70.76 km and 141.52 km CDM transmissions in each fiber core are shown in Figure 4. We can find that the BER values of all channels are lower than 2.1×10^{-2} after the 70.76 km transmission and remain below the SD-FEC limit after the 141.52 km transmission. This demonstrates that an ultra-high-speed 1.2 Tb/s optical signal with a PCS-64QAM modulation format can be transmitted error-free over 140 km in the field-deployed seven-core fiber cable. And some differences can be observed in the BER performance across different fiber core channels, which is mainly caused by the differences in span losses, inter-core crosstalk, and the performance of EDFAs among different fiber core channels. The BER performance of the ICS transmission channel using 200 Gb/s ICS OTUs is also experimentally investigated. The ICS signal uses a central wavelength of 1540.16 nm and is transmitted over the central core of the MCF. The results show that the ICS signal maintains a BER below 1×10^{-4} after the 141.52 km transmission, which can easily achieve error-free transmission after FEC.

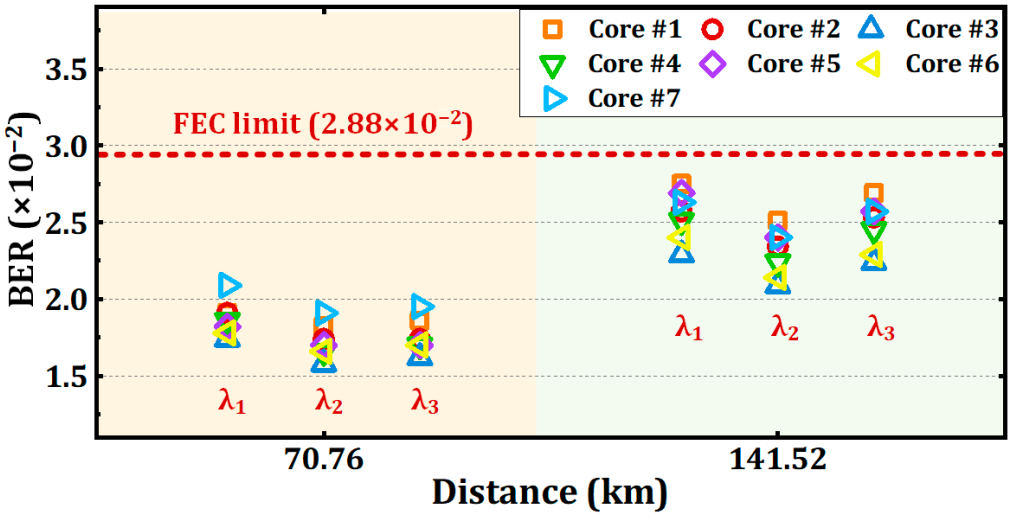

Figure 4. Measured BER values of the three tested wavelength channels after 70.76 km and 141.52 km CDM transmissions in each fiber core.

We then adjust the central wavelength of the 1.2 Tb/s OTUs across the C-band to evaluate the transmission capacity of the 1.2 Tb/s ICS CDM transmission system. The central wavelength of the ICS OTUs remains at 1540.16 nm, which is denoted as λ_4. The single-wavelength input power is still 8 dBm, and the ICS signal is also transmitted over the central core. The BER values of the 32 wavelength channels after the 141.52 km transmission are shown in Figure 5. And the normalized optical spectrum at the receiver is depicted in Figure 6. It can be obtained that the BER values of all 32 wavelength channels are below the SD-FEC limit for each fiber core. And the result of the ICS channel is not shown in Figure 5, which is because its BER is too low to fall within the display window of the figure. It should be noted that because the network management system can only show BER values at fixed intervals, the results displayed in Figure 5 are not continuous. These results demonstrate the feasibility of a real-time 267.8 Tb/s (1.2 b/s × 32 × 6 + 1.2 Tb/s × 31 + 200 Gb/s) transmission over a 141.52 km field-deployed MCF cable, which is a record real-time field ICS transmission capacity over deployed MCF cable just utilizing the C-band signals, to the best of our knowledge.

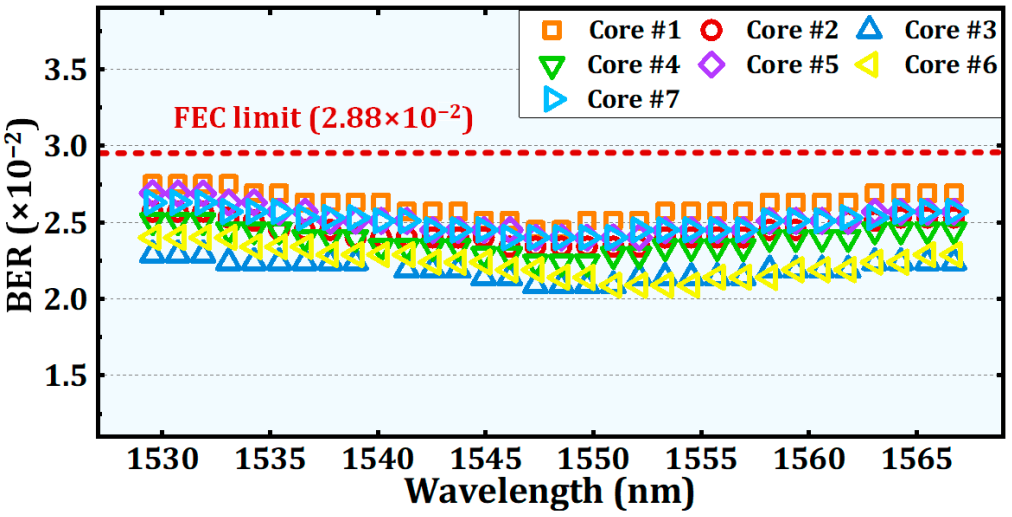

Figure 5. Measured BER values of the 32 wavelength channels after 141.52 km CDM transmission.

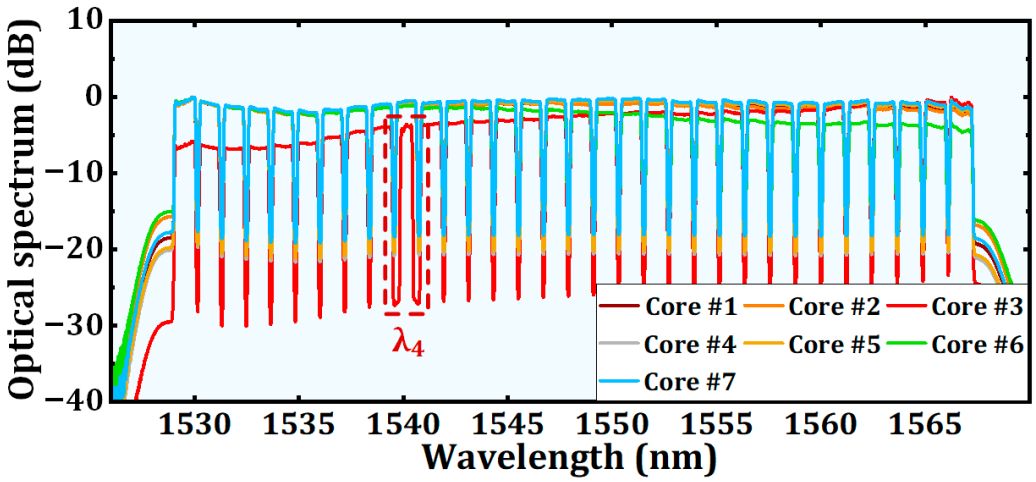

Figure 6. Normalized optical spectrum of the received 32 λ signals over the C-band.

Finally, the sensing ability of the ICS transmission system is also investigated in the field through the 200 Gb/s ICS signals at 1540.16 nm over the central core of the MCF. The 1.2 Tb/s OTN transponders and the ASE sources are also kept operating during this test. At this testing stage, we shake, periodically vibrate, and strike different positions of the overhead-installed MCF cable through a long rod, as illustrated in Figure 3e, and check the monitored results via the network management system. We conduct 200 tests for each type of disturbance, and the results show that the ICS system can accurately perceive and classify environmental disturbances to the cable in over 192 tests on average after approximately 5 s of sensing and processing. And the minor cases of undetected disturbances or the inaccurate identification of disturbances have no obvious correlation with the disturbance location but are primarily caused by a relatively low disturbance magnitude. The sampling SOP curves of the received signals when perceiving external shaking, periodic vibration, and striking are depicted in Figure 7a–c, respectively. We present three sampling SOP curves of the received signals for each kind of environmental disturbance with a time window of 2.5 s, which are obtained from the network management system. It can be observed that different types of disturbances will cause obvious changes, with distinct characteristics in the SOP of the received signals, which is the basis for our ICS system to sense and classify different types of external disturbances. Notably, during the experiments, we observe that relatively large-magnitude shaking or mechanical striking to the MCF cable is required to trigger external disturbance detection and alarm reporting at the receiver. This phenomenon primarily arises from the protective cable structure, which attenuates the impact of external disturbances on the SOP of the optical signals within the MCF. It is considered that this is actually reasonable, as only significant disturbances to the fiber cable, such as mechanical impacts or structural deformations, warrant prioritized attention in practical scenarios. Routine environmental factors such as natural wind exposure do not necessitate the triggering of an alarm. To further enable the detection of disturbances with different magnitudes, it is necessary to train the CNN model using disturbed optical signals collected from existing optical cable networks. These results indicate that the ICS system can simultaneously achieve ultra-high-speed data transmission and real-time monitoring and alerts concerns environmental disturbances, which is vitally important for next-generation ultra-high-speed highly reliable optical transmission networks.

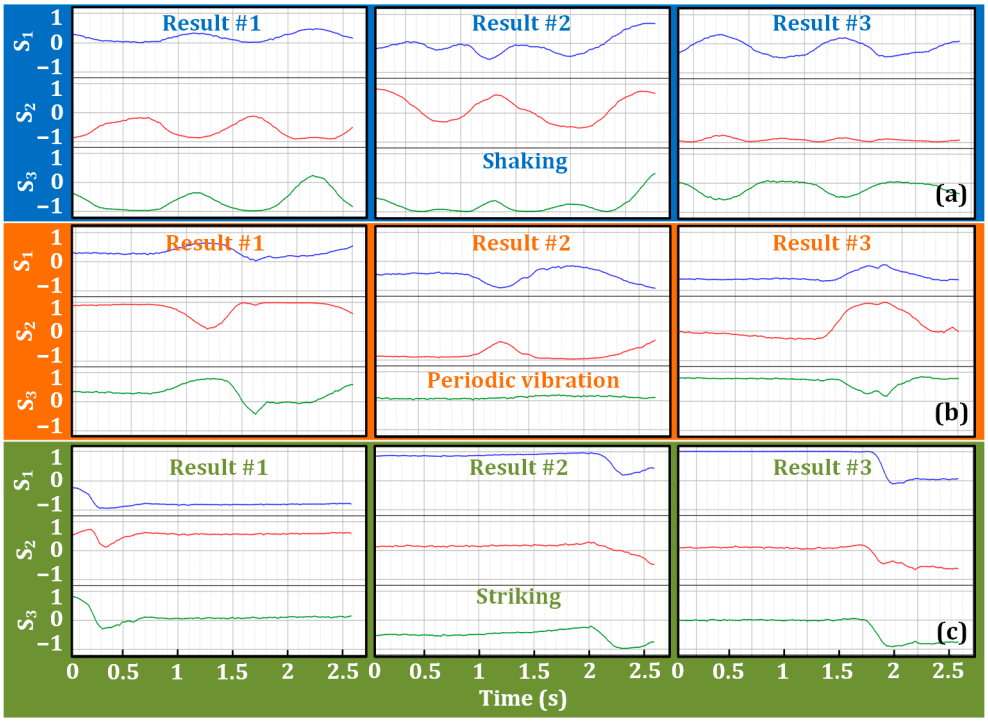

Figure 7. Sampling SOP curves of the received signals when perceiving (**a**) shaking, (**b**) periodic vibration, and (**c**) striking to the MCF cable.

6. Discussion and Prospection

In our field trial, we demonstrate the feasibility of a real-time 267.8 Tb/s transmission over a 141.52 km field-deployed MCF cable using only C-band 1.2 Tb/s OTUs. Since our L-band 1.2 Tb/s OTU is still under development, we do not investigate the transmission performance of ultra-high-speed 1.2 Tb/s signals over the L-band during this experiment. In addition, the 1.2 Tb/s OTU used in this trial can only be tuned across 32 wavelength channels within the C-band, which is fewer than that of the 400 Gb/s OTU with the same channel spacing in our we previous work [21]. These two limitations have prevented us from fully exploring the capacity potential of the MCF-based transmission system. Therefore, in our future work, we will first accelerate the research and development of C-band and L-band 1.2 Tb/s OTUs, whose central wavelength can be tunable across 40 wavelength channels over the C-band and L-band, respectively. Additionally, we will further investigate the transmission performance of the 1.2 Tb/s 80-wavelength 7-core WDM-CDM ultra-high-speed OTN system over the deployed MCF cable to fully explore its capacity potential and high-value application scenarios. And it can be foreseen that the impact of stimulated Raman scattering (SRS) must be considered in the C + L-band 80-wavelength transmission system [21]. And finally, we need to continuously develop photonic chips with higher modulation rates (e.g., 195-Gaud) to enable the 1.2 Tb/s OTU to adopt noise-tolerant lower-order modulation formats (e.g., PCS-16QAM), thereby extending the transmission distance of the system.

Regarding sensing capabilities, since the existing 1.2 Tb/s OTUs lack an integrated sensing functionality, we employ 200 Gb/s ICS OTUs to detect and classify external disturbances to the MCF cable. In future work, we will focus on integrating sensing capabilities into next-generation 1.2 Tb/s OTN systems to further enhance the transmission rate and performance of our ultra-high-speed ICS transmission system. Furthermore, we will retrain the CNN model using disturbed optical signals collected from existing optical fiber networks, which is a crucial step in promoting the field deployment of our ICS OTN system in existing networks. Moreover, unlike OTDR-based sensing systems, the SOP-based

sensing system utilized in our field trial cannot currently detect the location of external disturbances. Therefore, multiple extended capabilities, such as disturbance localization methods based on the SOP variations, need to be investigated in future studies. It should be acknowledged that this sensing method based on the SOP of received signals is an efficient way to perceive environmental disturbances and enable early warnings prior to fiber cable interruptions. We believe that it will be applied in high-value scenarios such as financial dedicated networks in the future.

7. Conclusions

In conclusion, we demonstrate an ultra-high-speed ICS OTN system utilizing 130 Gbaud PCS-64QAM 1.2 Tb/s OTN transponders and DP-QPSK 200 Gb/s ICS OTUs with an SOP-based sensing capability over a deployed MCF cable for the first time. A real-time 267.8 Tb/s 2 $\times$ 70.76 km ICS transmission is experimentally achieved using only C-band signals thanks to the high-performance 1.2 Tb/s OTN transponders. And the ICS system can sense external disturbances to the MCF cable such as shaking, striking, and so on through the 200 Gb/s ICS OTUs by monitoring changes in the polarization state of the received signals. To the best of our knowledge, the transmission capacity of this MCF-based ICS system is the highest among all real-time ICS field trials over a deployed MCF cable, and it can be further enhanced by incorporating L-band signals. This work demonstrates the feasibility of simultaneously achieving ultra-high-speed transmissions and the real-time sensing of environmental disturbances over field-deployed MCF cable, and it is beneficial to next-generation ultra-high-speed highly reliable optical transmission networks.

Author Contributions: Conceptualization, J.C., L.Z., Y.D., and Z.L.; methodology, J.C., Y.D., Y.W., C.Z., B.Y., and Y.C.; software, J.C. and L.Z.; validation, J.C., Y.W., L.Z., and Z.L.; formal analysis, B.H., B.W., and T.Z.; investigation, J.C., L.S., and L.Z.; resources, C.W., B.H., J.L., Y.S., Q.W., and N.G.; data curation, J.C., Y.D., Y.W., and Z.L.; writing—original draft preparation, J.C., L.Z., Y.D., Z.L., and C.W.; writing—review and editing, Y.S., C.C., and B.Y.; visualization, Y.D. and Y.W.; supervision, J.C. and Z.L.; project administration, J.C., Y.W., C.W., T.Z., L.Z., and C.C.; funding acquisition, J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Jian Cui, Leimin Zhang, Yu Deng, Zhuo Liu, Chao Wu, Bin Hao, Ting Zhang, Yan Sun, Qi Wan, Cheng Chang, and Ninglun Gu were employed by the company Department of Networks, China Mobile Communications Group Co., Ltd.; authors Yuxiao Wang, Bin Wu, Chengxing Zhang, Yong Chen, and Bing Yan were employed by the company Network Management Center, China Mobile Communications Group Shandong Co., Ltd.; authors Lei Shen and Jie Luo were employed by the company State Key Laboratory of Optical Fiber and Cable Manufacture Technology, YOFC. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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